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ABSTRACT

The first part of this report contains a critical summary of measurements of the atmospheric humidity in its upper layers (airborne investigations with the help of the condensation hydrometer, spectral investigations over England, measurements in the USSR). The report gives detailed descriptions, made by automatic balloon solar spectrophotometers, constructed at the Faculty of Atmospheric Physics, Leningrad University. The instruments registered the solar spectrum within the wide region of 0.4-13 μ. The spectra up to 25-28 km were recorded. The integral content of water vapor above different levels was defined by the bands 0.94, 1.13, 1.39, 1.87 and 6.3 μ. /66*

About 1 μ of water vapor was found above the level of 28 km on 23 October; other ascents confirmed a small content of water vapor in the stratosphere (the order of 10^{-6} g/g). In this connection the report critically considers the measurements in references 26-31. The authors

*Numbers given in margin indicate pagination in original foreign text.

have come to the conclusion that the humidity increase with height, obtained in separate investigations, is caused by the pollution brought in by the balloon and the apparatus. Analysis of all recent results of the measurements allows us to consider the conception of a humid stratosphere as groundless.

Study of the physical processes leading to the formation of noctilucent clouds is closely related to the investigation of many problems such as the characteristics of the temperature profile in the upper layers of the atmosphere, the radiation regime of the mesosphere, the gas and aerosol composition and the character of photochemical processes.

As is well known, until recently there were two separate basic hypotheses on the formation of noctilucent clouds: the dust and condensation hypotheses. Information on the upper atmosphere has been constantly supplemented with improvement of measurement methods and the means for sending instruments to great altitudes. Together with indirect surface optical investigations, there has been continuing development of methods for direct investigations of the profiles of temperature, pressure, atmospheric composition, scattering and velocity of air currents in the upper atmosphere. Data have also accumulated on stratospheric humidity. Preference has been given first to one hypothesis and then to another, as information accumulated on the upper layers of the atmosphere.

The first rocket investigations of the temperature profile revealed that at heights of about 80-85 km the temperature minimum is 220-230°K, but measurements made in recent years have considerably changed our ideas with respect to temperature in the mesopause region. With an increase of the accuracy of rocket investigations of pressure and temperature the temperature minimum in the mesopause region has been found to be increasingly sharply expressed. It was found that there is a seasonal variation of temperature, and it was established that the summer minimum of temperatures in the mesopause over latitudes to the north of the 45th parallel attains 150-160°K.

Whereas Ludlam (ref. 1), relying on the first measurements of the temperature of the mesopause and on some of the first reliable measurements of humidity above the tropopause (frost point 193°K), concluded that at a height of 80-85 km water vapor cannot attain saturation and that serious study must be made of the problem of the dust origin of noctilucent clouds, more recent temperature measurements of the mesopause have considerably strengthened the position of the supporters of the condensation hypothesis (refs. 2 and 3).

It should be noted that ground and rocket optical investigations of light scattering by the upper layers of the atmosphere also confirmed the long-standing suppositions of the supporters of the dust hypothesis concerning the existence of a layer of increased concentration of aerosols at heights of about 80-90 km. A. A. Dmitriyev and A. Ye. Mikirov (refs. 4 and 5) attributed the existence of this layer to a change of the character of settling of particles of cosmic origin in the mesopause region.

Experiments confirming the existence of a summer temperature minimum /67 of the mesopause at the latitudes of most frequent appearance of noctilucent clouds and the presence of condensation nuclei in the region of the temperature minimum still more reinforced the condensation hypothesis, and the final confirmation of the condensation-aerosol nature of noctilucent clouds in the summer of 1962 was not unexpected. A joint Swedish-American expedition in northern Sweden launched two rockets which carried aerosol particle traps; one of the rockets was launched into a noctilucent cloud. Investigation of the samples returned to earth revealed that both rockets trapped particles of cosmic origin and consisting of nickel and iron, but traces of ice coatings were discovered on some of the particles trapped in the region of the noctilucent cloud (ref. 6).

A record low temperature of the mesopause was found, $-130^{\circ}K$; thus, conditions existed for saturation of very small quantities of water vapor, of about $2 \cdot 10^{-5}$ g/kg.

As a result of confirmation of the condensation hypothesis, one of the timely problems now was a quantitative estimate of the moisture content of the high layers of the atmosphere and, of course, the mesopause, but this problem has not been solved until recently.

All our ideas on humidity in the region of the mesopause are based on measurements of humidity made by various methods used at heights not exceeding 30-32 km.

Some exception to this statement is the spectroscopic method. In addition to making possible determination of the humidity profile at the time of ascent, this method also makes it possible to estimate total moisture content between the instrument and the sun above the upper point of ascent of the instrument. Extrapolation of the humidity profile to great heights obviously involves errors which cannot be taken into account, but these evaluations until recently have been the only ones possible. Evaluation of the humidity in the mesopause region may involve still greater errors, because at this level the processes of photodissociation of water vapor molecules are of great importance. In the case of a static model of the atmosphere, Hesstvedt computed that above the 75 km level photochemical dissociation can decrease the concentration of water vapor molecules by several orders of magnitude (ref. 7). In a recent study (ref. 8) Hesstvedt attempted to estimate to what extent vertical movements in the atmosphere can change the height of propagation of water vapor molecules. In the computations he used as a point of departure the radiation model of circulatory processes in the upper layers of the atmosphere, taking into account the mechanisms by which heat is gained and lost; the model was proposed by Murgatroyd and Singleton and was reconsidered on the basis of new data on temperature in the mesopause. Preliminary data from the computations revealed that for the high latitudes and the summer mesopause there is a predominance of ascending currents, and the humidity at the mesopause level, at least in transient processes, can be sufficient for saturation. It must be stated that these computations are of an approximate character due to the inaccuracy of the radiation model.

In this same study, on the basis of data from a slow-motion motion picture survey of noctilucent clouds made by Witt, Hesstvedt attempted to compute the rate of growth of ice particles in a cloud and found that in order to explain the observed wave movements it is necessary to assume enormous values for specific humidity in the noctilucent cloud--about 1 g/kg, which contradicts the results of computations of the photochemical destruction of water vapor molecules at these heights.

The need for further investigations of the processes involved in humidity at great heights is obvious, but as already mentioned, humidity measurements at lower levels are the basis for estimates of humidity at the higher levels. The mentioned initial measurements of humidity, made over England as early /68 as 1942, were supplemented by measurements made by other authors. However, the specific humidity values measured by different methods in the stratosphere by a number of authors during the last 20 years, while in satisfactory agreement for the troposphere, differ by several orders of magnitude with ascent into the higher layers. The theories of a "moist" and "dry" stratosphere have appeared, and the degree of stratospheric humidity is the subject of lively discussion. It is obvious that a change of tropospheric humidity should somehow influence the layers above the tropopause, but the enormous scatter of data forces us to assume that the measurement results are complicated by some other factor which is not taken into account by some authors and which introduces errors into the measurements. Therefore, below we will consider the results of stratospheric humidity measurements made by different methods. We will discuss in detail measurements demonstrating a low stratospheric humidity, especially the measurements made at the Clarendon Laboratory.

Aircraft Investigations of Humidity with a Frost-Point Hygrometer

It has long been known that measurements of relative humidity in the stratosphere, using standard hair and membrane hygrometers, are unreliable because of an increase of inertia and decrease of sensitivity of the humidity sensors when measuring insignificant quantities of moisture at low temperatures. As early as 1937 Gol'tsman developed a frost-point hygrometer for use with a balloon. Different modifications of this instrument have been used until recently for stratospheric measurements.

The investigators at the Clarendon Laboratory of Oxford University have done a great deal of work studying the humidity of the lower layers of the stratosphere. The frost-point hygrometer developed by Dobson and Brewer (ref. 9) was first used on a high-level aircraft to altitudes of 12 km in 1942. Measurements of the frost point in the atmosphere were accompanied by careful laboratory investigations of the character of precipitation onto the mirror (polished metal surface) in the hygrometer. The authors found that the precipitate on the mirror of the frost-point hygrometer can remain in the form of supercooled water to a temperature of 240°K. The mirror therefore was cooled still more and heated to almost complete disappearance of the precipitate. The two temperatures of increase and evaporation of the precipitate were recorded while holding the mirror at such a temperature that the precipitate did not increase and did not evaporate. The authors used the average of these temperatures as the ice point. The authors emphasize that at low temperatures it is possible to maintain the temperature of the mirror one or two degrees below the true ice point without formation of a precipitate; in this work the experience and training of the observer are of great importance. Investigations by photoelectric methods of the rate of condensation in relation to the temperature of the mirror and air humidity have shown that there is a natural lower limit of the temperatures below which humidity measurements are impossible with the existing method. The deposit on the hygrometer at a temperature below 194°K has a glassy appearance and is therefore invisible. With heating this glassy ice is slowly transformed into crystalline ice. The authors noted a considerable decrease of the rate of growth of the precipitate with approach to this "critical" temperature of the ice point. With a decrease of air humidity and a decrease of the ice point the sizes of the crystals became less, and there was an increase of the distance between them.

The scientists at the Clarendon Laboratory have also carefully investigated other effects which make measurements difficult at low temperatures, such as the "activation" of the surface of a mirror held at a low temperature, accelerating the appearance of a precipitate even at an ice point of 190°K and /69 frequently disappearing with brief heating of the mirror. In this case the precipitate appears on the mirror very slowly. The variability of "activation" made it difficult to get the same values twice in succession.

Laboratory tests have shown that when all precautions are taken the frost-point hygrometer gives reliable results to an ice point of 194°K.

Since 1942 the frost-point hygrometer has been used repeatedly for measuring humidity to heights of 11-12 km. Flights were made on a high-level aircraft of the British Meteorological Service; humidity measurements were made by experienced observers with the necessary practice and familiarity with the equipment.

The first measurements revealed that the ice point decreases to a height of 11 km and at that level attains a temperature of 193°K (scaled to a specific humidity of $2 \cdot 10^{-3}$ g/kg). In many cases at the upper flight levels the precipitate on the mirror became indistinguishable. Above the tropopause the ice point and air temperature diverge sharply, which indicates a considerable decrease of humidity with transition into the lower layers of the stratosphere.

Dobson proposed that the pressure of the measured air be increased in order to obtain more reliable data in the lower stratosphere. If the air pressure is raised to normal, the ice point can be increased by 20°, which will prevent the undesirable effects observed during measurements of the "critical" temperature.

After jet aircraft were available to the meteorological service, Goldsmith (ref. 10) proposed that the jet aircraft compressor be used for this purpose. The surface of the compressor is small in comparison with the volume of air intake, and its use should not introduce significant measurement errors. In actuality, in the preliminary flights the measurements of the ice point with and without the use of a compressor were compared. The measurements made at different pressures confirmed that the compressor does not introduce significant errors (ref. 11).

Measurements with a modified hygrometer, carried out in 1950 by Murgatroyd, Goldsmith and Hollings (ref. 12) to heights of 15 km, confirmed the dryness of the stratosphere. The authors found that with increasing height the ice point decreases, but tends to a constant value, which on the average was $188.5^{\circ}K$. Seventy flights were made at different seasons of the year, at different latitudes, from Iceland to North Africa (ref. 13). All measurements revealed that above the tropopause the air contains little moisture and the mixing ratio averages $2 \cdot 10^{-3}$ g/kg.

Dobson attributes the dryness of the stratosphere to the fact that the moist air carried aloft into the stratosphere by ascending currents in the equatorial region loses a considerable quantity of moisture by a freezing-out process and is transported into the middle latitudes. It was found that even in air from which condensation nuclei have been removed the formation of ice crystals is easy at temperatures below $232^{\circ}K$. However, the temperature of the stratosphere in the tropical latitudes can attain $182^{\circ}K$. Dobson notes the fact that the measured ice point in the stratosphere in the middle latitudes is close to the lowest temperature in the tropopause region over the tropics, which serves as one of the demonstrations of the tropical origin of air in the stratosphere in the middle latitudes.

Spectral Investigations of Humidity in the Lower Stratosphere over England

Spectral investigations of the absorption of solar radiation in the free atmosphere were begun at Oxford in 1952. The results of the first flights of

Yarnell and Goody (ref. 14) to heights of 11 km had a qualitative character. A number of atmospheric absorption spectra were recorded with a prism infrared spectrometer with a tracking system for guiding the solar rays into the entrance slit of the instrument. The absorption bands of water vapor (6.3 μ), CO_2 (4.3 μ), O_3 (4.75 μ) and CH_4 (7.8 μ) were recorded with a mean resolution of 0.1 μ. The authors concluded that water vapor absorption above 11 km is approximately equal to a 2 m thick layer of moist air at normal pressure. Jones and Roberts continued investigations of the solar spectrum with better resolution. The CH_4 and $C^{13}O_2^{16}$ absorption bands were investigated, but no quantitative measurements of water vapor absorption were made. The authors noted that the 2 ν_2 band virtually disappeared from the solar spectrum at a height of 10 km (ref. 15). /70

In 1957 Houghton and Seeley began systematic investigations of absorption of optically active components of the atmosphere by use of a vacuum spectrometer with a high resolution of about 2 cm^{-1}. The spectrometer had a photoelectric tracking system, mounted on the wings of the aircraft. The instrument was carried aloft to heights of 15-16 km; these measurements may therefore be considered as essentially the first measurements made in the stratosphere. Investigations of absorbing gases in the atmosphere were accompanied by careful laboratory investigations of the absorption of the investigated gas in relation to pressure and concentration. A multipass vessel was constructed for this purpose, and laboratory investigations were made using the same instrument used in the stratosphere.

Multiple measurements of water vapor absorption on the optical path between the sun and instrument supplemented the data obtained with frost-point hygrometers in the lower stratosphere. It was discovered for the first time that above 15 km there is an equivalent precipitable layer of water of about 5 μ. On the assumption of a constancy of specific humidity of still higher layers of the stratosphere, the authors found that the specific humidity above 15 km falls in the range $1 \cdot 10^{-3}$-$4 \cdot 10^{-3}$ g/kg (ref. 13).

The humidity profile measured by Houghton and Seeley to heights of 15 km agrees well with the profile obtained with an ice-point hygometer carried on this same aircraft.

Humidity Investigations Above 15 km

Both spectral measurements and measurements with a frost-point hygrometer were made by British investigators to heights not exceeding 16 km aboard an aircraft. Estimates of the humidity of still higher layers, nevertheless, involves assumption of a constancy of specific humidity at different heights. The Clarendon Laboratory therefore developed a light instrument which could be carried to heights of 25 km by a small balloon.

Williamson constructed a simple instrument weighing only 2.5 kg, making it possible to measure the counterradiation of the still higher layer of the atmosphere in the region of the absorption band of water vapor centered at 6.3 μ (ref. 16). The radiation detector was a germanium sensor, alloyed with gold and covered with an indium antimonide filter. The spectral sensitivity of the instrument fell in the limits of the water vapor absorption band. The detector, in front of which a vibration modulator was placed, was housed in a chamber constituting an ideally blackbody with a small aperture oriented at an angle to the vertical to prevent the entry of radiation from the balloon envelope into the detector. The chamber was submerged into a Dewar vessel containing liquid air. The instruments were carried aloft at nighttime in a cloudless sky. Signals were transmitted through a telemetric channel. The results were interpreted by a statistical model of the water vapor absorption band; absorption was computed taking the Curtiss-Godson approximation into /71 account. An allowance was made for effects associated with the radiation of foreign gases in the region of the water vapor absorption bands.

As an example the author cites the results of an ascent on 10 September 1963 to a height of 25 km. The temperature of the ice point between 12 and 25 km fell from 196 to $185^{\circ}K$; the specific humidity was approximately constant, beginning at 12 km, and averaged $3 \cdot 10^{-3}$ g/kg. Williamson notes good agreement between the specific humidity values which he measured in the lower layers of the atmosphere and radiosonde data. Above the tropopause the absolute values of atmospheric radiation, as noted by the author, approach the results of spectral investigations of atmospheric radiation obtained in the free atmosphere by Hampson over Canada (ref. 17).

Recently investigations of stratospheric humidity made by the Clarendon Laboratory have been supplemented by measurements with an electrolytic hygrometer carried aloft in a small balloon. The idea for constructing such a hygrometer was expressed by Brewer in 1958. In reference 13 Houghton briefly describes the principle of operation of this instrument.

Two platinum electrodes, embedded in quartz, were covered with phosphoric acid, which served as hygroscopic material. Water vapor molecules, reaching the surface of the electrodes, induce a current proportional to the quantity of molecules.

The measurements made by Goldsmith in the stratosphere over England also revealed a constancy of specific humidity with a value of approximately $1.5 \cdot 10^{-3}$ g/kg. Unfortunately, the absence of more complete information makes it impossible to draw any conclusions concerning the reliability of the values measured by this instrument.

In generalizing the results of the British investigations, made with these methods, it can be concluded that these measurements agree well with one another. It has been determined that the specific humidity of the stratosphere is low, and its values remain constant with height and fall in the range $1 \cdot 10^{-3}$-$4 \cdot 10^{-3}$ g/kg.

Stratospheric Humidity Measurements in the USSR

These investigations were begun in 1955 under the direction of B. S. Neporent. Different modifications of spectrometers operating in the near-infrared region of the spectrum were developed (ref. 18). The basis for the spectrometers was a high-transmission monochromator having an autocollimation system and a diffraction grating with 300 lines/mm. Sunlight entered an entrance slit and was reflected from a dull aluminized plate. Signals were transmitted to earth through a telemetric system.

The first version of the instrument made it possible to detect fixed wavelengths situated inside and outside the water vapor absorption bands. The absorption bands 1.4 and 1.88 μ were discriminated. The wavelengths 1.24, 1.5 and 2.2 μ were recorded as index wavelengths. Later the investigated part of the spectrum was broadened and there was a changeover to continuous recording of the entire part of the spectrum. Resolution of the instrument was 180 Å. In addition to the solar spectra, "zero" signals were transmitted to earth, corresponding to a closed entrance slit, as well as calibration signals determining the scale of the record of the spectrum and characterizing the operation of the radioelectronic part of the instrument, signals of the pressure and temperature sensors, etc. The sensitivity of the spectrometer was equalized for the spectrum, and the spectra of a standard light source were recorded periodically for checking the sensitivity of the spectrophotometer.

Measurements were made at diferent sites in the Soviet Union. The instruments were carried aloft in balloons to heights of 16-17 km. Processing /72 of the first measurements revealed that humidity decreases with height, but above the 12 and 17 km levels virtually the same quantity of water vapor was observed--about 50 μk(ref. 18). The authors attributed this fact to some shortcomings of the apparatus. Measurements in the 1.4 μ band were possible only to a height of 11 km. Complications of the instrumentation did not make it possible for the authors to consider the data obtained at heights greater than 11-14 km as reliable. Later the authors concluded that the humidity of a column of the atmosphere above 15 km is negligibly low. The observed absorptions, remaining constant with ascent to the upper point, the authors attributed to the possible influence of adsorbed moisture in the instrument (ref. 19). At levels above the tropopause it was determined that the specific humidity decreases. Whereas at the 10 km level the mean specific humidity was $4 \cdot 10^{-1}$ g/kg, at 15 km it had decreased to $2 \cdot 10^{-2}$ g/kg.

In 1964 the specialists of the Department of Atmospheric Physics of Leningrad University prepared for launching into the stratosphere an automatic balloon-borne complex of solar spectrophotometers to record the solar spectrum in a broad range--from 0.4 to 13 μ. Three prism spectrophotometers overlapped this spectral region and could operate simultaneously. The resolution of the spectrophotometers averaged 70 Å in the visible region of the spectrum, 30 Å in the near-infrared and 0.1 μ in the infrared region of the spectrum (at 10 μ) (ref. 20). The entrance slits of the spectrophotometers were illuminated by the mirror of a biaxial photoelectric servomechanism with a circular zone of sensitivity and three degrees of motion, the most important of which ensured pointing of the system at the center of the solar disk with an error of ±5' (ref. 21).

The group of spectrophotometers was controlled by a single programming apparatus. The monochromator for the infrared region of the spectrum was supplied with a mechanism for compensating the decrease of solar intensity with wavelength. This was achieved by a change of the width of the entrance and exit slits. The water vapor absorption band therefore was recorded without distortion.

The program provided for the recording of solar spectra on the oscillograph tape at different scales, periodic checking of the sensitivity of the receiving-recording part of the apparatus, periodic recording of the spectrum of an artificial light source for determining the water vapor content within the monochromators on the basis of water vapor absorption in the 1.87 μ band, and recording of different voltages, recording the temperature of different components of the instrument package, recording temperature, pressure and humidity outside the package, etc.

The absolute values of direct solar radiation were also recorded. A Yanishevskiy actinometer was mounted on the axis of the tracking system for this purpose. Temperature of the actinometer was recorded for determining the temperature corrections. The full cycle of measurements continued about three minutes. The cycles followed one another without interruption.

In 1964 there were three launchings of spectral apparatus together with a group of actinometric instruments for measuring the radiation regime (ref. 22). The launchings were made on 11 and 22 July and 23 October 1964. The spectra were recorded to heights of 25-28 km. The summer ascents were made under anticyclonic conditions; the autumn ascent was made under worse weather conditions with a complete cloud cover of stratus clouds at a height of about 2.5 km. The quality of the spectra to the tropopause was good. In the tropopause region the instrument package experienced sharp swaying and rotation. Analysis of some spectra was difficult, because during the swaying of the instrument package the area of the section of the solar rays reflected by the tracking system mirror could not always completely cover the entrance slit of the spectrophotometers. However, above the tropopause the instrument package gradually became less restless, and again entirely satisfactory spectra were obtained. /73 The instruments operated normally, except on the second ascent, during which prior to the launching there was a malfunction of the amplifier lamp of the spectrophotometer operating in the near-infrared region of the spectrum. This part of the spectrum could not be recorded, and therefore the water vapor concentration within the package remained undetermined.

For the first time data were obtained on the character of the attenuation of solar radiation in the stratosphere in a broad region of the spectrum at heights up to 28 km, as well as information on absorption of higher levels.

The analysis of humidity data was made for parts of the spectrum, including the absorption bands of water vapor and carbon dioxide, since their absorption bands overlap. Total absorption was measured by graphic interpolation. The data were processed using known interpolation formulas derived by Howard and his associates in reference 23, and taking into account the results of laboratory investigations of the forbidden absorption bands of water vapor and carbon dioxide. These investigations were made for mixtures of an absorbing and foreign gases at different total and partial pressures at different temperatures. In particular, it was demonstrated that total absorption in the band depends slightly on temperature; therefore, the influence of temperature was not taken into account in our computations. The dependence of absorption on partial pressure of water vapor was also not taken into account because it was small, especially in the stratosphere.

First records of water vapor absorption on the optical path within the instrument package between the artificial light source and the radiation detector (spectra of an incandescent lamp were recorded each three cycles of measurements of solar radiation) were analyzed. It was assumed in the computations that the pressure within the package is equal to the pressure outside (the package had thermostatic control, but was not airtight).

The results were unexpected: during the entire ascent the moisture content remained virtually constant. In the first ascent, on the optical path of the ray within the instrument package there was 26-27 μ of an equivalent layer of precipitable water; in the third, 25-26 μ. This effect was caused by the influence of the moisture adsorbed by the foam plastic of the instrument package and the parts of the apparatus. The water vapor content, despite the presence of an opening in the package for entry of the solar rays, was not decreased, and above 20 km the water vapor absorption in the solar spectrum was determined almost completely by the moisture trapped in the stratosphere together with the apparatus.

In determining the humidity of the above-lying layers in the stratosphere, in addition to determining the moisture, it was necessary to exclude the absorption of CO_2 (for example, in the region of the 1.87 μ band there are two CO_2 bands: 2.01 and 2.05 μ). The selective absorption of CO_2 was excluded by both graphic and computational methods. In the second case the exclusion of CO_2 absorption was accomplished with the Howard equations, with the assumption of an additive character of absorption in the H_2O vapor and CO_2 bands and postulating an invariable relative CO_2 concentration of 0.032 percent. The Curtis-Godson approximation was used in the computations, and the effective pressure of carbon dioxide was computed as the mean weighted pressure of the higher CO_2 layer.

The correctness of the computations was checked by an analysis of data on the total CO_2 absorption in the 4.3 μ band, where no appreciable water vapor absorption is observed. Comparison of the computed and measured values of total absorption in this band revealed good agreement between them at heights above the tropopause (the discrepancy was not greater than 4-7 percent). In the troposphere the discrepancies caused by overlapping of the CO_2 and H_2O bands were significant (25 percent at the earth's surface), but after allowance for /74 N_2O absorption these data agreed for the troposphere with an error of 10 percent.

The total water vapor content in the layer of the atmosphere above different measurement levels was determined from the water vapor bands 0.94, 1.13, 1.39, 1.87 and 6.3 μ. Humidity measurements on the second ascent were made only for the 6.3 μ band. Since humidity measurements were not made within the package on the second ascent, allowance for contamination of the package by water vapor trapped in the stratosphere was based on the averaged results of the first and third ascents. The humidity within the three containers was almost identical in these ascents, and there was no basis for assuming that the conditions of the second ascent were different from the conditions for the others.

The computations of humidity were based on the mean weighted pressures, determined in the troposphere by data obtained using the humidity sensor of a radiosonde. The value of the mean weighted pressure in the troposphere was approximately equal to 0.8 of the pressure at the next measurement level, which corresponds to an exponential decrease of the water vapor concentration with height. In the stratosphere the coefficient 0.5 was used on the assumption of constancy of specific humidity at different heights.

Figure 1 shows the dependence of the moisture content of a column of the atmosphere on height, obtained using the measurements of 23 October 1964. The data were obtained using absorption measurements in all recorded bands. About 1 μ of water vapor was observed in the layers above 28 km. The results of the first ascent were the same; the second ascent was only to a height of 25 km, but it also revealed a low water vapor content in the stratosphere. The relative measurement errors increase with height due to the small values of absorption and the increasing influence of the water vapor present inside the package. The error in determining water vapor at the upper level was reckoned at 100 percent. Obviously, incorrect choice of mean weighted pressure also should exert an influence on the measurement results.

We also note that the use of interpolation functions obtained by Howard under laboratory conditions at total and partial pressures are different from the real values observed in the atmosphere and also involves errors, but their evaluation is a separate problem. We note only that the dependence of integral absorption as determined by Howard has the form of a square root law for weak absorption. It follows from modeling experiments that the square root law, in a case when lines having the Lorentz contour do not overlap and are faint, should be replaced by the law of linear dependence of total absorption in the lines of the band on the concentration. It is difficult to make a quantitative check of this effect; in any case laboratory measurements of absorption of

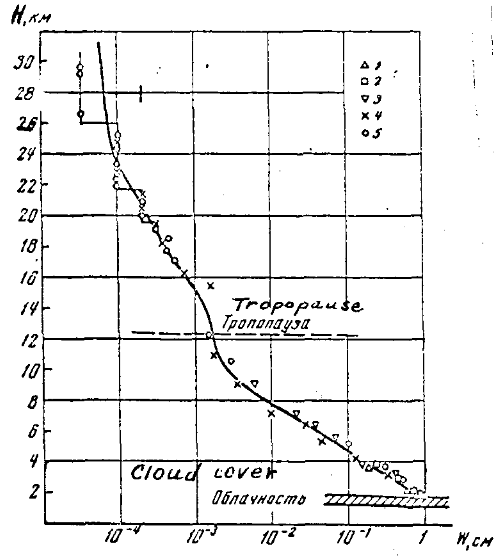

Figure 1. Water vapor content above different levels; data for ascents of 23 October 1964. 1, 0.94 μ; 2, 1.13 μ; 3, 1.39 μ; 4, 1.87 μ; 5, 6.3 μ.

increasingly small quantities of water vapor at negligibly small partial pressures have not succeeded until recently. The reason for this is the enormous difficulty in quantitative measurements of small concentrations of water vapor because of its adsorption by the walls of the container and parts of the monochromator. /75

The use of the square root law in the case of weak absorption obviously results in somewhat understated values of humidity measurements at great heights. However, the use of the functions obtained purely theoretically is presently impossible. Quantum mechanical computations of the line intensities of a number of bands now have only been started.

We will now consider the values of the specific difference at different heights obtained on the basis of scaling the curves of total moisture

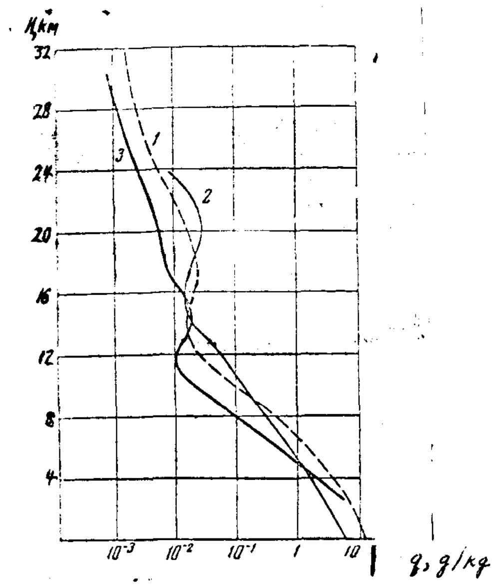

Figure 2. Change of specific humidity q with height. 1, 11 July 1964; 2, 22 July 1964; 3, 23 October 1964.

content of the atmosphere. These data were obtained for all three ascents (fig. 2).

Stratospheric specific humidity decreases considerably with height and continues to decrease to heights of 12-14 km, where it attains values of about 10^{-2} g/kg. A low humidity minimum is observed at heights of about 12-14 km (which agrees well with the measurements made at the Clarendon Laboratory). Above 24 km the specific humidity decreases to values of 10^{-3}-$5 \cdot 10^{-3}$ g/kg, which also agrees with the reduced results of other authors. Comparison of the values of specific humidity and the humidity values obtained over England shows that in the region of 15 km the humidity measured over England was somewhat lower than that observed over the USSR. With ascent into the stratosphere both British and Soviet measurements show a "stabilization" of specific humidity (of about 10^{-3} g/kg to $5 \cdot 10^{-3}$ g/kg).

Data on the insignificant moisture content of the stratosphere have also been obtained recently by Gates (ref. 24). By sending aloft a vacuum spectrometer with a high resolution to a height of 30 km in a balloon (31 March 1964 in Texas), Gates discovered above 30 km a 2 μ equivalent of precipitable water, which, taking measurement errors into account, agrees well with the measurements made by the authors of this study.

A decrease of specific humidity with height was also observed by Camming (ref. 25). The author flew over Canada in an aircraft at altitudes of 9.7, 12.2 and 13.7 km. The measurements were made in the water vapor band 2.7 μ /76 with a monochromator with a diffraction grating. Camming notes that at a height of 13.7 km the contamination of aircraft apparatus by water vapor attains 30 percent.

Generalizing the results of the measurements cited above, it may be concluded that they demonstrate a decrease of specific humidity with height in the troposphere and its relative constancy in the stratosphere with values of about 10^{-3} g/kg. Using as a point of departure the constancy of specific humidity, it seems indicated to compute the conditions of water vapor saturation for the higher levels.

Figure 3 shows the change of the ice point with height to the 100 km level, using the results of measurements on balloons. The ice point decreases with height to values of about 180°K at 30 km. As already mentioned, the temperatures in the region of a noctilucent cloud are about 130°K, which corresponds to a water vapor saturation for a specific humidity in the region of the mesopause of 10^{-5} g/kg. The ice point, computed for the mesopause level on the assumption of constancy of specific humidity with height, is 150°K, which is entirely adequate for saturation. Obviously, the destruction of water vapor

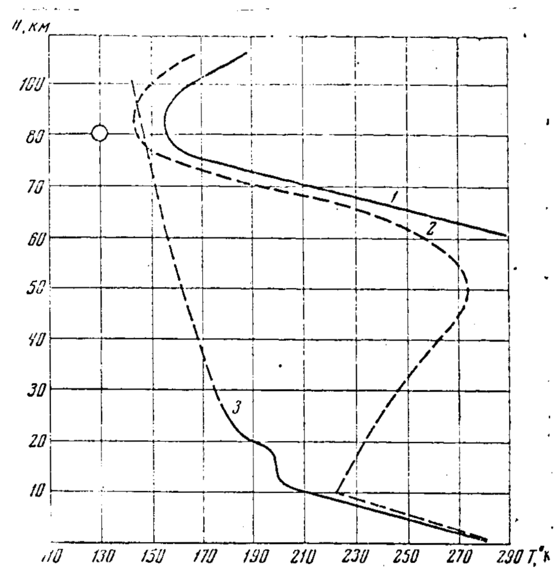

Figure 3. Vertical profiles of temperature and ice point. 1, Temperature according to data in reference 2; 2, temperature according to data in reference 3; 3, temperature of ice point according to ascents made by specialists of Leningrad State University; circle designates temperature determined during launching of rocket into noctilucent cloud (ref. 6).

molecules as a result of photochemical dissociation will exert a considerable influence on the concentration of water vapor molecules at this level, but even a decrease of humidity by a factor of 50-100 times does not exclude the possibility of saturation at the observed temperatures in the region of noctilucent clouds. The temperatures measured in the stratosphere in the absence of noctilucent clouds (for example, in ref. 2) cannot cause water vapor saturation in the region of the mesopause, even without allowance for the photochemical decomposition of molecules.

Measurements of Increased Stratospheric Humidity

We will briefly discuss the measurements which show that the specific humidity in the stratosphere increases with height. In 1955 Murcray and his associates (ref. 26) developed an automatic balloon spectrometer which was first carried aloft to 30 km on 22 June 1955. The instrument was designed for measuring the absorption of the forbidden bands of water vapor and carbon dioxide. The solar rays were directed into the instrument slit by a tracking system having an error of ±15'. The heat-insulating housing had a single aperture for admitting the sun's rays into the spectrometer. The instrument was airtight.

Several ascents were made in balloons, but various factors did not make it possible to obtain any reliable data on stratospheric humidity until 19 July 1959. On that day a spectrometer was carried aloft to 30 km. Total absorption in the water vapor band 6.3 μ was measured. Computations of specific humidity for heights above 30 km revealed that the sepcific humidity values over the instrument were in the range $1.5 \cdot 10^{-1}$-$3.4 \cdot 10^{-1}$ g/kg. The authors concluded that above 30 km over New Mexico there was at least 20 μ of precipitable water. The measurements were accompanied by determinations of the ice point with a frost-point hygrometer. These data are reliable to heights of about 13 km, where the ice point was found to be 203°K. At greater heights the temperature was lower and the instrument ceased to operate (ref. 27).

A comparison of the apparatus used by Murcray with the apparatus developed by Leningrad University shows that these instruments are similar, but Murcray did not measure humidity within the instrument package. It is entirely obvious that a rise of water vapor within the instrument package, not taken into account, creates the spurious effect of an increase of specific humidity with height in the region of low pressures. The 20 μ of water vapor obtained by the author almost do not apply to the higher layer of the stratosphere. Houghton agrees with this. He computed that if the temperature within the package /77 was 20°C, the relative air humidity within the container is 50 percent. Murcray found 10 μ of water vapor per meter of the length of the optical path within the instrument in the stratosphere. The example of an ascending frost-point hygrometer which failed to operate at the heights at which Dobson encountered effects making measurement of the ice point difficult is also instructive.

We note that the authors of this study sent aloft an optical instrument and a frost-point hygrometer, but it systematically ceased to operate or gave incorrect readings upon approaching the stratosphere.

Whereas the specialists of the Clarendon Laboratory applied considerable efforts in measuring stratospheric humidity at heights of about 15 km, American investigators, in studying the upper layers of the stratosphere, sent aloft simpler and lighter instruments on balloons. With ascent into the upper layers there was a considerable change in the conditions for ventilation of the chamber of the frost-point hygrometer.

The efficiency of ventilating apparatus decreases by two orders of magnitude by a height of 30 km, which necessarily exerts an influence on the results. The contaminations created by the appratus are more dangerous than in the case of spectral measurements, because it is difficult to make a direct determination of the released vapor. During ascent the balloon and all instruments release water vapor. The instrument rises in the wake left by the balloon, and the hygrometer capsule can be penetrated by nonstratospheric water vapor. Whereas the spectral instruments measure the moisture content on a sloping path between the sun and the instrument and the sector which the ray passes through near the balloon is short, the balloon-borne frost-point hygrometer continuously sucks in air situated near the apparatus. We note also that the ice point is so low (according to our computations in the 30 km region the ice point decreases to 180°K), that the ice precipitated onto the mirror, according to Dobson, should have a glassy structure. However, balloon-borne hygrometers do not have a compressor of the type used by Goldsmith.

In measuring atmospheric humidity, Barret et al. (ref. 28) at a height of 15 km obtained a decrease of specific humidity to values of 10^{-2}-$5 \cdot 10^{-2}$ g/kg, but above this level they found an increase of the specific humidity to 0.1-0.15 g/kg. Some of Barret's measurements do not reveal an increase of specific humidity in the 30 km region, but nevertheless the values are considerably greater than those measured by the spectroscopic method.

The authors of reference 28 also observed large variations of the ice point during ascent. Mustenbrook and Dinger, in reference 29, also discovered variations of the ice point aloft. At heights of 14-16 km they found a specific humidity of $2 \cdot 10^{-3}$ g/kg, which agrees well with spectral measurements, but by 30 km the specific humidity, nevertheless, increased to 0.08-0.1 g/kg. Barclay, Elliott et al. (ref. 30) sent a water vapor trap aloft to heights of 27 km; this trap was a tube submerged in liquid hydrogen through which air was sucked. The water vapor was frozen together with the carbon dioxide, and the quantity of solid carbon dioxide served as a measure of the air passed through the instrument. Assuming that at a height of 27 km the relative concentration of CO_2 is 0.026 percent, the authors found a specific humidity of $3.7 \cdot 10^{-2}$ g/kg, which is an order of magnitude greater than the values determined by the spectral method.

Broun and Rybus, in reference 31, who measured stratospheric humidity over Antarctica, also found an increase of specific humidity at heights greater than

13 km. The scatter of values for the ice point was great and could attain 40-50°K at levels very short distances apart. The authors note that the moist wake of the balloon can influence ice-point measurements. The scatter of points indicates measurement errors rather than atmospheric stratification.

In reference 13 Houghton indicates that recent measurements made by Mustenbrook with a balloon-borne frost-point hygrometer have directly demonstrated that the increase of specific humidity with height is caused by contaminations introduced by the balloon and apparatus. It was discovered for the first time by carefully prepared investigations that at heights of about 30 km a frost-point hygrometer is also capable of measuring low stratospheric humidity. The values of specific humidity determined by Mustenbrook fall in the range $2 \cdot 10^{-3}$ g/kg (ref. 8). /78

We also note a study by Brasefield (ref. 32), who measured the moisture content of the stratosphere with a hygristor, an instrument whose sensor was a film of electrolyte, consisting of a saturated solution of LiCl applied to a glass base. The author found that specific humidity increases with height to a value $3 \cdot 10^{-1}$ g/kg at 24 km, but errors of the method do not make it possible to consider these data reliable, if for no other reason than that the instrument is capable of operating only at relative humidities greater than 15 percent. However, in the stratosphere the relative humidity is considerably less. Thus, it can be stated that an increase of specific humidity with height was measured using an instrument not suitable for work where there is a low water vapor concentration. These results therefore are unreliable. However, these measurements are used extensively in formulating different models of the atmosphere. For example, Gutnick (ref. 33), in generalizing the results obtained by Barret, Brasefield, Murcray, the early measurements of Mustenbrook and Dinger, and others, formulated a model of the stratosphere in which specific humidity increased by 30 km to values 10^{-1} g/km. M S. Malkevich, using these same data, also concluded that the specific humidity in the stratosphere is high (ref. 34).

After analyzing all recent measurement results it can be stated that the concept of a moist stratosphere is unfounded.

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